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Three-detector setup for PAL spectrometer based on DRS4 waveform digitizing board*

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A digital three-detector positron lifetime spectrometer was developed. It consists of a DRS4 waveform digitizing board and three $LaBr_3$ scintillation detectors coupled to XP2020Q photomultiplier tubes. DRS4 waveform digitizing allows data sampling at up to 5 GSPS with high amplitude resolution, with good time scale linearity and stability. In the triple-coincidence, the new system could reach a 195 ps time resolution, which is better than the conventional analog apparatus with the same detectors. This spectrometer can be applied to the other scintillation timing measurements with picoseconds accuracy.

Keywords: Digital lifetime spectrometer, Timing, triple-coincidence, Waveform sampling, DRS4 chip

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I. INTRODUCTION

Positron annihilation lifetime (PAL) spectrometer is a useful technique for studying defects in condensed matter [1–3], and its time resolution is an important parameter. Efforts have been made to improve the time resolution [4–7], using new scintillator, new data acquisition system and new timing technology. A conventional PAL spectrometer consists of a pair of scintillation detectors, two constant fraction timing discriminators (CFD), a time-to-amplitude converter (TAC) and a multi-channel analyzer (MCA), with a time resolution of about 200 ps or a little better [8]. However, performance of conventional PAL spectrometers is limited by the analog electronics devices.

With the rapid development of electronics and digital signal processing technology [9, 10], some authors used fast digitizer or digital oscilloscope to build a new type of PAL spectrometer–digital positron lifetime spectrometer (DPLS) [11–14], with better time resolution and simpler structure. The DRS4 chip, which was designed at the Paul Scherrer Institute, Switzerland [15, 16] is a switched capacitor array (SCA) capable of sampling 9 differential input channels at a sampling speed of 0.7–5 GSPS. Characteristics of the high channel density, high analog bandwidth of 950 MHz, and low noise of 0.35 mV make this chip ideally suited for high precision waveform digitizing. For simplifying the design process to integrate the DRS4 chip into custom electronics, an evaluation board has been designed at USTC. It is basically equivalent to a 4-channel 5 GSPS digital oscilloscope. In this paper, a simplified DPLS using a DRS4 evaluation board is designed and tested.

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II. EXPERIMENTAL AND ANALYSIS METHODS

The detectors were $LaBr_3$ cylindrical crystals wrapped with Teflon tapes, coupled to XP2020Q photomultiplier tubes (PMT), and encapsulated in duralumin cups. The start detector was Φ36 mm × 20 mm in size, while the other two stop detectors were 36 mm × 15 mm (set for 1275 and 511 keV γ-rays, respectively). The PMTs were biased at -1.8 kV, which is considerably lower than the maximum rating value (-3 kV). A ^{22}Na source of ∼93 kBq (∼25 µCi) activity was used (Fig. 1).

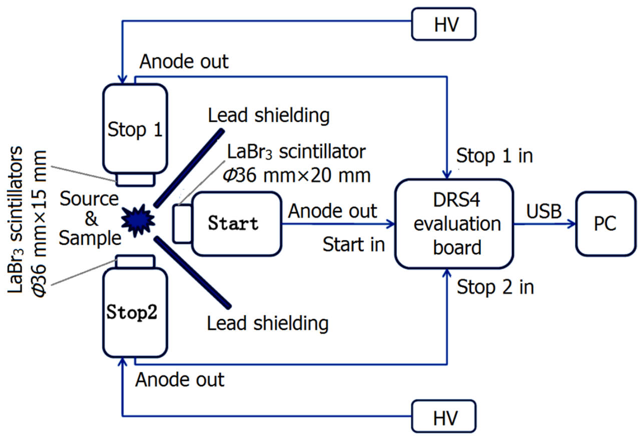

Fig. 1. (Color online) Schematic diagram of the digital positron annihilation lifetime spectrometer (DPLS).

The start and stop detectors were angled at 90°, while the two stop detectors were at 180°. Compared with a two-detector system, the three-detector system has a double stop system, and flight time of the paired annihilation photons flying in opposite direction can be detected, so as to obtain an accurate “stop time” (the average time from the two stop detectors). With this improvement, the lifetime spectrum is closer to reality and the time resolution of three-detector

system is better than that of the two-detector system. A lead shielding plate was placed at the center of the start and stop detectors. This reduces the Compton scattering effects between the three detectors, and the lead shielding plate absorbs the back scattered γ-rays. The count rate with a given source activity depends on the measurement geometry. In this experiment, the actual count rate reached $25\,\mathrm{s}^{-1}$.

In Fig. 1, the DPLS consists of three detectors and a DRS4 evaluation board. Anode pulses of the PMTs are sent to Ch2, Ch3 and Ch4 of the DRS4 evaluation board. The input signals are converted to discrete waveform data, which are stored in memories of the DRS4 evaluation board after trigging condition is satisfied, and transferred to the PC by USB 2.0 bus. The maximum transfer rate is about 20 MB/s. Then, the waveform data are analyzed and constructed to positron lifetime spectra. The DRS4 evaluation board in fulfilled trigging mode on Ch2, Ch3 and Ch4 receives the signals when the voltages all exceed the rated amplitude at the same time. Pulses of the two stop detectors are delayed for 4–8 ns with a delay cable. Several methods are used in the waveform digital processing to construct the positron lifetime spectrum by histogramming the time interval between pulses of the start and stop detectors after pulse discriminator.

A. Pulse discrimination methods

The first step of data processing is to discriminate the eligible waveform pulses. The deformed and distorted waveforms should be removed. Several pulse discrimination algorithms are used to pick up the eligible pulses for timing analysis.

1. *Methods to eliminate bad waveforms*

Distorted waveforms (over two waveforms accumulated in one channel) should be eliminated and eligible pulses be chosen by pulse shape discrimination algorithm of peak searching algorithm and baseline discrimination method. The former finds the peak position and peak amplitude in the waveform, while the latter chooses appropriate level of baseline waveform. The two methods can effectively select suitable waveform.

2. *Pulse area discriminator methods*

In some works, total energy of the measured pulse is proportional to the sum of all created scintillation photons [17], and the pulse area between the digitized waveform and baseline is the relevant γ-ray energy. The pulse area is calculated by summing the amplitude of each channel over the whole waveform range. The energy spectrum of the ^{22}Na source measured by the digital PAL spectrometers is shown in Fig. 2(a), with energy resolutions being 3.7% at 0.511 MeV and 3.2% at 1.275 MeV, while Fig. 2(b) shows the energy spectrum obtained using an analog system with the same detectors, with the energy resolutions being 5.85% at 0.511 MeV and 4.73% at 1.275 MeV. The digital system is better, and the pulse area discriminator is used to select the pulse pair of 1.275 MeV and 0.511 MeV.

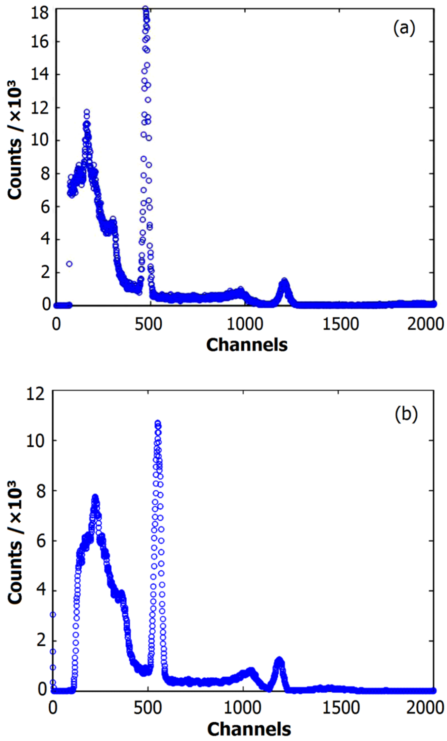

Fig. 2. (Color online) Energy spectra of ^{22}Na source measured with digital (a) and analog (b) positron annihilation spectrometer.

B. Digital constant fraction timing analysis methods

After checking that the anode pulses fit in predetermined energy (pulse area) window, timing analysis will extract the time information from the digitized pulse groups. It is generally believed that the timing algorithm for scintillation detectors is constant fraction timing. The method is to analyze numerous leading-edge-timing measurements according to the moment that represents the minimum time jitter when the pulse crosses a certain constant fraction level f_{cf} of its full amplitude. The optimum fraction is a characteristic of the detectors, scintillators and PMT types.

A Gaussian function can well describe the leading edge of a pulse [11, 18]. Since Gaussian fitting is a non-linear interpolation, so a log transformation is done to the waveform amplitudes to obtain the new waveform data, which are fitted with a second-order polynomial interpolation as a replacement of Gaussian fitting. The fitting range is 40 samples in the leading edge of the pulses. The dependent parameters of the time resolution are studied on both the fitting range and timing fraction. The curves are obtained by varying the fraction for one detector and by keeping the fraction constant for the other. The optimum constant fraction is about 30% with both detectors [11, 17].

C. Building positron annihilation lifetime spectra

Triple-coincidence requires a good double-stop system. Performance of the DRS4 evaluation board was tested using two signals, of the same pulse parameters but the time delay, from a signal generator. Then, two signals from the stop detectors are used to test the double stop-system. Figure 3 shows a typical waveform of two signals from the signal generator recorded by the DRS4 evaluation board. The sampling rate was set to 5.12 GS/s, the two signals of the same parameters had a time delay of 10 ns. The minimum and maximum time delays are 9.917 ns and 9.947 ns, respectively, with mean standard deviation is of 2.5 ps. The system has a good timing synchronism and it can be used to the triple-coincidence PALS.

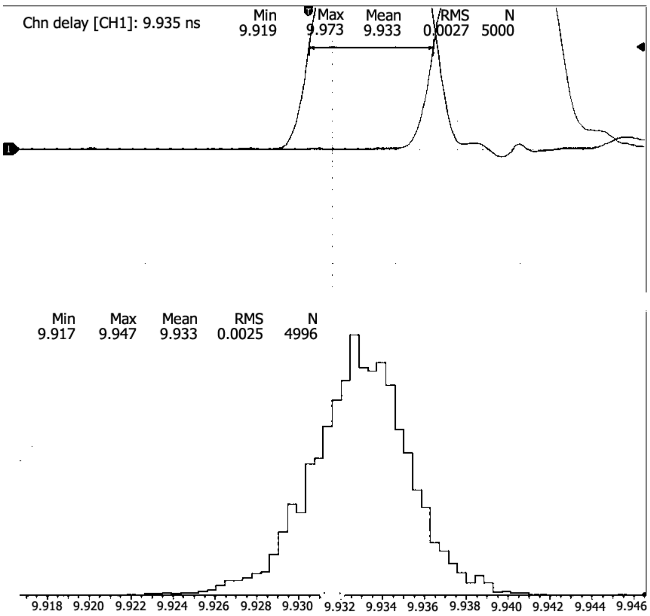

Fig. 3. The time interval of the two output signals from the signal generator recorded by DRS4.

The same delay cable was used to the two stop detectors. The two stop signals recorded by the DRS4 are shown in Fig. 4. The sampling rate was 5.12 GS/s. The stop detectors signals in black is PMT1 and the red one is PMT2. The two signals have the same rise time and time delay, and they have an excellent signal synchronism.

After selection of γ-ray energy by pulse amplitude discrimination, frequency distribution of Δt is calculated as

$$\Delta t = t_{\text{stop}} - t_{\text{start}}, \quad (1)$$

where, $t_{\text{stop}} = \frac{[t_{\text{CF}}(\text{PMT2}, 0.511\,\text{MeV}) + t_{\text{CF}}(\text{PMT3}, 0.511\,\text{MeV})]}{2}$, $t_{\text{start}} = t_{\text{CF}}(\text{PMT1}, 1.28\,\text{MeV})$. In addition, only those that satisfy $[t_{\text{CF}}(\text{PMT2}, 0.511\,\text{MeV}) + t_{\text{CF}}(\text{PMT3}, 0.511\,\text{MeV})] < 450\,\text{ps}$ are accepted.

The PAL spectra are constructed by the frequency distribution of Δt. Figure 5 shows two PAL spectra collected in the single-stop and double-stop systems respectively, each containing about 1 million counts. Only about 500 channels around the peak of the spectra are presented for comparison.

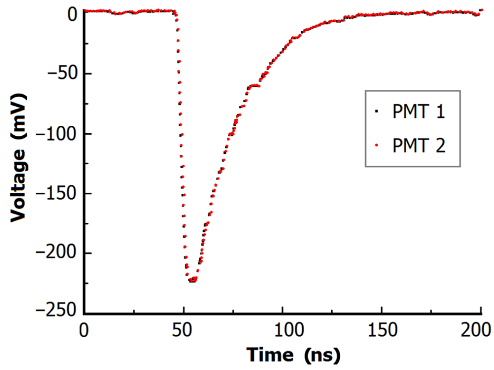

Fig. 4. (Color online) Two anode output signals from the XP2020Q PMT recorded by DRS4.

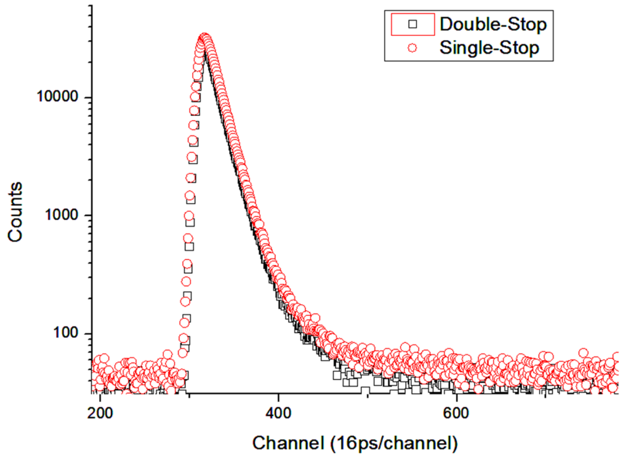

Fig. 5. (Color online) PAL spectrum for bulk silicon obtained with the double-stop and single-stop systems. Background is not subtracted.

III. RESULTS AND DISCUSSION

PAL spectra for bulk Si were measured to test the spectrometer performance. After analyzing the PAL spectra, t_1 ((220.0 ± 2.8) ps) is due to free positrons in the sample which is in agreement with Ref. [19], while t_2 ((495.0 ± 8.7) ps) and t_3 ((2235.0 ± 46.3) ps) is due to the source components. The time resolution of the double-stop system is 192 ps (FWHM), being better than the single-stop system, which is a face-to-face detector geometry with a symmetry axis passing through axis of the two detectors. Background of the double-stop system is lower than the sing-stop one.

Dependence of time on energy of the incident γ-rays was measured for 11 days using ^{60}Co (1.33 MeV and 1.17 MeV) with 2.6×10^4 counts. The time resolution for the ^{60}Co cascade radiations was (175.0 ± 1.4) ps. The energy range was set to $1.0\,\text{MeV} < E < 1.5\,\text{MeV}$, and the time spectrum is

shown in Fig. 6. A better time resolution was obtained with narrower energy window settings at the cost of the counting rate decrease.

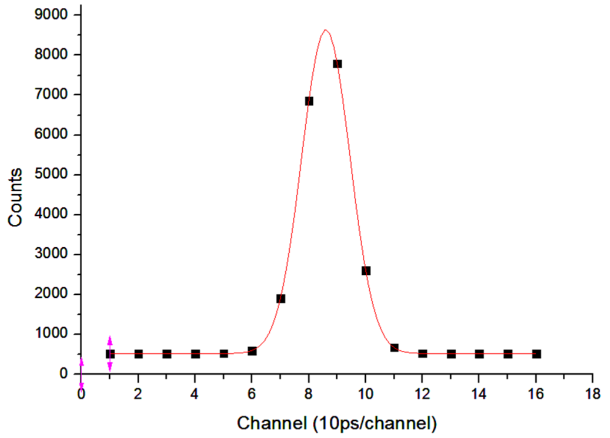

Fig. 6. (Color online) Time resolution spectrum of ^{60}Co source measured with the digital positron annihilation lifetime spectrometer.

Table 1 lists time resolutions for different conditions of double-stop PAL, single-stop PAL and ^{60}Co.

TABLE 1. Time resolutions (in ps) of different conditions

Resolution	Single-stop PAL	Double-stop PAL
Time resolution	206	192
^{60}Co resolution	182	175

IV. CONCLUSION

A digital positron annihilation lifetime spectrometer composing of three $LaBr_3$ scintillation detectors and a DRS4 evaluation board was developed. For ^{60}Co spectra, time resolution of the DPLS with double-stop is about 175 ps. With its good performances and stability, the DPLS has prominent advantages over other positron annihilation spectrometers.

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